headaches, insomnia, and emotional lability. Psychologic testing was normal. A 21-year-old man experienced nondisabling irritability, insomnia, and headaches. Psychiatric and psychologic interviews yielded inconsistent results. The diagnosis was posttraumatic stress disorder.

Nerve damage has been reported in exposed appendages. Fleck (1983) summarized findings of nerve damage in the hands and forearms of a woman who was using a microwave oven that apparently malfunctioned. According to the report, at the end of a cooking cycle she reached into the cavity to retrieve a dish and was purportedly exposed to the output of a 600-W oven for 5 seconds. The nerve damage persisted resulting in pain and heat sensitization of nerve fibers. Apparently no evaluation was made of the microwave oven. Dickason and Barutt (1984) also observed nerve damage, persistent pain, and hypersensitivity to light touch in a woman overexposed while cooking with a microwave oven. In this case, the oven was evaluated and found to be malfunctioning. Exposure lasted 60 to 90 seconds. Ciano et al. (1981) reported paresthesia in the hand of a cafeteria waitress exposed to a malfunctioning microwave oven over the span of 3 days. Tintinalli, Krause, and Gursel (1983) also noted paresthesia in the hand of a man who received a momentary exposure to a malfunctioning microwave oven. Thirty minutes postexposure, the hand was nonresponsive, pale, and cold. Sixty minutes after exposure, the hand responded normally.

Hocking, Joyner, and Fleming (1988) evaluated an incident where a nine-man radio lineman party was exposed to 4.139-GHz microwaves while disconnecting a waveguide from a metal gantry. Estimates of the power density for the two members who experienced the highest exposures were 4.6 mW/cm^2 at 2 m for about 90 minutes. The estimated skin SAR was 3.8 W/kg, while the whole-body average SAR was 0.13 W/kg. The other men were exposed at < 0.15 mW/cm^2. Claims of behavioral effects, temporary sexual impairment, insomnia, irritability, and loosening of scalp hair were made by the high-exposure group. Behavioral effects were also claimed by members of the low-exposure group. The authors conclude that medical "examinations have found various, slight (but inconsistent) abnormalities in the staff which could not be related to the high or low level of exposure. It is concluded that this exposure of up to 4.6 mW/cm^2 at 4.1 GHz for nearly ninety minutes has not resulted in harmful effects."

3.5.8.3 *Reproductive Effects*

Rosenthal and Beering (1968) reported a case of male infertility. This was attributed to microwave exposure because the individual worked for four years as a maintenance man on energized weather radar systems. He reported sensing the feeling of warmth, but it is not possible to place this in the proper context because no exposure data were provided.

Rubin and Erdman (1959) summarized four cases of the clinical application of 2.45-GHz microwave diathermy to treat pelvic inflammation. Two patients were treated during pregnancy. One of these spontaneously aborted but subsequently became pregnant and delivered a healthy baby. The other patient had a normal baby. The other two were treated prior to pregnancy, and both delivered normal infants.

A microwave oven repairman had plastic induration of the penis, which the investigators note had not been associated with MW exposure. However, they could not "discount a true casual relationship to microwaves." No degenerative testicular changes were observed. Abdominal exposure (2.45 GHz) was reported to be 18 mW/cm^2 (Rose et al. 1969).

3.5.8.4 *Skin Effects*

Ciano et al. (1981) observed necrosis of the skin in a young woman who operated a plastic welding machine. Her hand had been caught in an energized sealer for approximately 2 seconds. Damage was extensive, and the hand nonresponsive, which resulted in amputation.

In the case report by Lim et al. (1993), mention is made of facial erythema in a maintenance technician. However, no exposure data are given that would positively link this to microwave exposure. As mentioned earlier, the actual power density emitted from the dish antenna is not known, although estimates from normal operation would be low. Computer modeling of a worst-case leak during normal operation (30 mW/cm^2) would produce a small temperature rise (0.48°C) that "could not realistically cause the reported injury" (Hocking, Joyner, Fleming, and Anderson 1994). At a lower frequency, 2.45 GHz, Rose and colleagues (1969) have reported a "thermally-induced erythema *ab igne*" in microwave-oven repairmen with facial exposure around 20 mW/cm^2, although the duration of exposure is not clear (*ab igne* means the erythema is localized and due to heat). Gellin (1971) terms this facial radiodermatitis, which includes erythema and "a sense of heat."

There was no report of a sensation of heat or pain in the account by Lim et al (1993), although other reports of erythema in the literature commonly include such descriptions. In the report by Fleck (1983) of exposure to the hands and arms due to a malfunctioning (600 W) consumer microwave oven, the subject perceived the exposure as follows: "She felt a hot pulsating sensation and burning in all fingers and finger nails, as well as a sensation of 'needles' from forearms to fingers." Subsequently she experienced erythema, edema, and "jabbing pain." In another case where a microwave oven malfunctioned, the subject "experienced a sudden burning pain of the radial side of her hand" and later developed redness and swelling (Dickason and Barutt 1984).

Brodkin and Bleiberg (1973) reported two cases of cutaneous damage associated with microwave oven use. The women, who worked at a snack bar, exhibited deformity and ridging of the fingernails. Both women operated the same oven and the onset of the damage occurred at the same time. It is not clear how long the women were exposed, but there appear to have been multiple instances of exposure over a number of months. During the purported exposure, there was no sensation of heat or pain or report of erythema or edema, which would be expected. It was alleged that the oven was malfunctioning, but an evaluation could not be performed, because it had been returned to the manufacturer. Following this, the "lesions began to improve when the unit was removed."

Hocking, Joyner, and Fleming (1988) report loosening of scalp hair in a group of radiolinemen, but this was not linked to RF exposure.

A number of occurrences of painful skin damage associated with spark discharge have been investigated by federal OSHA inspectors (Hagaman 1989a; Shepich 1990; Heins 1990). Tissue damage occurs when RF energy is rapidly released just prior to skin contact with a conductive object in which the incident RF field has induced currents. One occurrence was when construction workers were building a highway in Hawaii beneath a coast-guard navigation antenna. "Radio frequency signals transmitted from the antenna may induce a perceptible electrical charge in large rubber tire vehicles, construction equipment and ungrounded metallic structures" (Hagaman 1989a). An energy threshold of more than 15 μJ was believed to be necessary to produce the effect (Hagaman 1989b). Similar problems were also reported for longshoremen who contacted RF-energized parts of cranes and cables. In these reports the RF sources were AM radio station transmitting towers (Shepich 1990; Heins 1990; Heins and Curtis 1990).

3.5.8.5 *Death*

A case of death related to microwave exposure near a radar transmitter was reported by McLaughlin (1957). The individual reported extreme tenderness and pain in the abdominal cavity. Upon admission to the hospital, the patient received an appendectomy but died ten days after the operation. Merckel (1972) and Ely (1971, 1985) have disputed McLaughlin's claim that this death was associated with overexposure to MW radiation. Merckel (1972) attributes it to appendicitis. Ely (1985) notes that at the operational frequency (10 GHz), there would have been considerable skin damage due to the shallow penetration depth, and this was not observed by McLaughlin.

3.5.8.6 *Cancer*

Archimbaud and colleagues (1989) in Lyon, France, reported a single case of acute myelogenous leukemia in a 46-year-old man who had repaired 3-kW microwave oven generators for a number of years. Thirty to thirty-six generators were repaired weekly, and part of the process required that power be supplied to each generator was for about 1 minute. The patient estimated that he was exposed about 5 min/d to microwaves from an unprotected generator. No other exposure information (location, distance, power density, etc.) was provided. In conclusion, Archimbaud et al. state, "Intense exposure to microwave radiations should therefore be considered as a potential aetiology of secondary leukaemia."

This conclusion has been criticized by Jauchem (1990) for lack of exposure information and how the literature cited by Archimbaud et al. (1989) in support of their conclusion was interpreted. In a response, Archimbaud (1990) explained that during exposure, the patient "was standing on the side of the generator while testing it by heating a glass of water" and that "he did not recall any abnormal heat sensation," which would be expected with high-level exposure at this frequency. In a critique, Hocking and Garson (1990) note that deep burns and cataracts would also be expected with intense exposure.

A concern has been raised dealing with the potential for cancer associated with exposure of law enforcement personnel to the microwave emissions from traffic radar units. A number of reports have been published in trade journals, and these have included anecdotal accounts of a small number cases of cancer, primarily ocular, skin, and testicular (Poynter 1990a, 1990b; Gibbons 1991; Clark 1991; Zaret 1991). This has been the basis for one lawsuit (*Bendure* v. *Kustom Signals, Inc.*), where the jury found for the radar gun manufacturer because "the officer's cancer was a slow-developing illness that could not possibly have manifested itself only a few years after exposure, as alleged by the plaintiff" (BNA 1993). As noted in Section 3.5.6.1, Davis and Mostofi (1993) have reported an excess of observed versus expected testicular cancers in a cohort of policemen.

That these cancers could be caused by police radar units seems rather unlikely for a number of reasons. First, police radar units are low-power systems, having operational powers similar to a child's walkie-talkie (IEEE 1992b). Second, the exposure levels, as addressed in detail in Chapter 5, are very low. For example, according to Fisher (1993), the operator will be exposed at levels less than 1% of the power density at the aperture (< 50 $\mu W/cm^2$) unless: (1) there is a considerable reflection of the microwave energy, which should only occur when the reflector is closer than 365 cm (12 ft), (2) an energized unit is placed in one's lap, or (3) the operator inadvertently exposes himself. Third, the maximum anticipated exposures do not represent overexposures when compared with values recommended in state-of-the-art exposure documents. For example, if one should receive an exposure such as that described in (2) and (3), the maximum power density Fisher (1993) determined (6.4 mW/cm^2) is less than the allowable human exposure criteria (10 mW/cm^2) for the applicable averaging time (IEEE 1992a). Furthermore, as Fisher (1993) has pointed out, use of these devices at such close distances to the body will modify the impedance, which will reduce the radiated energy because of an impedance mismatch between the radiator and the local environment. Fourth, the penetration depth at these frequencies (10 to 35 GHz) is minimal, resulting in energy that is absorbed largely topically. Fifth, since microwaves have not been shown to be mutagenic, they should not be viewed as tumor initiators. Some animal studies have pointed to the possibility that MWs may be tumor promoters, but this needs more study. Sixth, epidemiologic studies of radar and microwave workers have not identified any statistically significant differences with cancers in general or the specific cancers mentioned earlier. The radar and microwave workers included in these studies had the opportunity to be exposed at higher values of power density at a larger range of frequencies than users of traffic radar units. And last, the few animal studies that have been carried out near these frequencies have demonstrated thermal effects (Hagan and Carpenter 1976; Rosenthal et al. 1976), but at substantially higher power densities than reported for radar guns.

A similar concern has been voiced concerning brain cancer and exposure to microwave energy from low-power, portable cellular phones. This occurred after the initiation of legal activities following a single case of brain cancer in a cellular phone user. The spouse of the user brought the lawsuit based upon his perception that exposure to microwaves had caused his wife's cancer. This received national attention when the issue was discussed on the "Larry King Live" talk show on Cable News Network (Fischetti 1993).

Portable cellular phones generate about 600 mW at frequencies between 800 and 900 MHz. Although locally high values of power density may exist near the antenna, most studies have indicated that the penetration depth is low, and local SARs usually do not exceed the exposure limits (FCC 1993). However, recent studies have demonstrated differences in dosimetry, and these differences appear to depend somewhat on methodology, i.e., the use of mathematical models versus the use of tissue-equivalent phantoms, and distance from the antenna. The exact reasons for these reported differences need to be determined.

With the present state of understanding, it does not seem likely that brain cancer would be caused by exposure to these devices (FDA 1993). However, there are some significant gaps in the scientific data base, but these should be filled when well-designed animal studies and epidemiology studies are completed. At the operational frequencies, it has been demonstrated that microwave radiation produces thermal effects. Although the specific frequency band and modulation types used by portable cellular phones and other cellular devices have not been included in studies of microwave-induced cancer in test animals, studies at 2450 MHz have not established microwaves as tumor promoters.

3.5.8.7 *Summary*

The incident reports indicate that overexposure to high levels of radio-frequency radiation may result in nerve damage and skin damage. It is possible that the finding of Hirsch and Parker (1952) is a case of microwave-induced cataracts, but the other reports are not consistent and do not establish a reliable link with microwave exposure.

3.5.9 Cutaneous Perception of Microwaves and RF Burns

Perception of microwave energy involves cutaneous thermal sensation or pain and demonstrates a frequency dependency at the few frequencies studied. Power densities necessary to produce threshold warmth sensations were lower at 10 GHz than at 3 GHz, for a forehead surface area of 37 cm^2 (Hendler 1968; Hendler, Hardy, and Murgatroyd 1963). This is probably due to the shallower penetration depth at the higher frequency, where more of the energy is absorbed in a smaller volume near the surface of the skin. Michaelson (1972) estimates that at 10 GHz, a thermal sensation is evoked when the entire facial skin is exposed at slightly more than 4 to 6 mW/cm^2 for 5 seconds or approximately 10 mW/cm^2 for 0.5 seconds (Michaelson 1972).

Justesen and colleagues (1982) exposed the forearm of male and female volunteers to 2.45-GHz microwaves. The SAR, estimated by measurement of the temperature in the middle of a saline-filled latex balloon, was 0.076 $W/kg/mW/cm^2$. Average thresholds of perception for women and men were 25.27 mW/cm^2 and 28.88 mW/cm^2, respectively. The values for the six participants ranged from 15.40 to 44.25 mW/cm^2. The researchers also exposed four of the volunteers to infrared radiation, finding that they could not tell the difference between a thermal stimulus provided by the microwaves and IR radiation. A comparison between the two spectral regions showed that the perception thresholds differed by about a factor of 5, with 10.16 J of microwave energy and 1.8 J of IR radiation necessary for perception. Hence, more MW energy is necessary to perceive warmth than infrared energy.

Cook (1952) demonstrated that the threshold data for pain at 3 GHz varies from 0.83 to 3.1 W/cm^2, dependent upon the exposure duration, for an exposed area of 9.5 cm^2 (Cook 1952). However, according to Michaelson (1972), the perception of pain is "independent of the area of exposure, radiation intensity, exposure time, and anatomical site" and is related to a critical skin temperature.

Gandhi and Chatterjee (1982) determined the magnitude of the electric field that would produce short-circuit currents in common objects. Generally, the necessary E-field strength varied as a function of frequency and the object being irradiated. For example, perception (let-go in parentheses) currents were produced if a roof, fence, car, and truck were irradiated at, respectively, 250 (1040), 160 (850), 80 (440), and 20 V/m (110 V/m), between 10 to 100 kHz. The E-field strength then decreased with increasing frequency up to 10 MHz. Further work by Chatterjee, Wu, and Gandhi (1986) examined perception and let-go currents for finger and grasping contact, as discussed in Chapter 2. Average threshold perception currents for men were around 40 mA ($\sim$ 50 mA for pain) for finger contact from 0.1 to 3 MHz. Perception thresholds for women were lower than those for men. For example, with grasping contact, women were around 95 mA from 0.1 to 3 MHz, while men were around 120 mA. Ten-year-old children were estimated at about 60 percent of the values for male adults.

In a study of shipboard RF, Rogers (1981) found an average RF burn hazard threshold current around 200 mA between 2 and 20 MHz. According to Osepchuk (1992) "For body impedance 500 Ω, the burn threshold corresponds to 20 watts dissipated in a few seconds in a volume of 1 cc."

Comparison with "conventional" burns, Budd (1985, 1992) notes that RF burns may involve deeper body tissues because of the greater penetration depth. Clinicians have observed that undamaged layers of fat may be sandwiched between damaged layers of skin and muscle. Hot spots may be formed, producing areas of high local absorption leading to local tissue necrosis. It is possible that there may be a latency period between exposure and development of effects. Although the picture is not clear, Budd notes that there may be some clinical differences between RF burns and conventional burns.

3.6 OTHER POTENTIAL HAZARDS

3.6.1 Metallic Implants or Objects

A few studies have evaluated the interaction of radio-frequency and microwave energies with metal implants or metal objects worn by people. A list of some of these objects is in Table 3-16. Metallic objects may perturb the field, concentrating the RF energy in the vicinity of the conductive object. This may lead to localized heating, such as that observed by Feucht, Richardson, and Hines (1949). These researchers found that wire implants and metal plates increased measurable temperatures in in vitro and in vivo experiments with 2.45-GHz microwaves. Larger temperature increases were observed when metals were closer to the surface and with larger metal plates. Murray (1984a) reported an incident where a man wearing a transdermal nitro patch received a second degree burn the size and configuration of the patch. Apparently this occurred when energy from a recently serviced microwave oven heated the patch's aluminized plastic adhesive strip. A carpenter with a steel plate in an index finger used "a diathermy machine which was used to dry glue on lumber." This resulted in pain and swelling when the finger was exposed (Merckel 1972).

Table 3-16. Devices That May Enhance or Be Affected by RF Fields

Cardiac valves
Pacemakers
Metal staples
Insulin infusion systems
Orthopedic wires, plates, and rods
Transdermal delivery system
Cochlear implants
Metal-framed spectacles
Jewelry, watches

Hocking, Joyner, and Fleming (1991) examined the interaction of RF fields with metal implants, including both heating and interference. Interference has been observed in cardiac pacemakers and cochlear implants. A number of reports and reviews are available, although with the evolution in design of pacemakers and RF sources, the reports are primarily of historical interest (Elmqvist 1976; Reis 1979). Sources of interference that have been identified include microwave ovens (Bonney, Rustan, and Ford 1973; King et al. 1970; Rustan, Hurt, and Mitchell 1973), microwaves in general (Osepchuk 1971), radar (Bonney, Rustan, and Ford 1973; Rohl et al. 1975), and diathermy units (Marshall, Scott and Peaston 1990). Obviously, interference is of great concern in the health care environment where there are numerous devices that produce RF and ELF fields, and there is a relatively high density of individuals at risk.

In the RF part of the spectrum, pacemaker interference is usually controlled by signal filtering and shielding the device. However, interference is still possible. With the complexity of today's pacemakers and RF sources, a thorough evaluation usually requires a case-by-case approach. Factors that must be considered include the operational frequency of the RF device, whether or not the fields are pulsed, and the design of the pacemaker (Grant 1993a). This approach is amenable to the industrial environment where there are usually few individuals at potential risk, but it may not be a viable approach in a hospital. To illustrate the importance of proper selection of the pacemaker and electrode, Grant (1993b) has discussed two scenarios where pacemaker wearers experienced relatively high exposures to low-frequency magnetic fields and RF fields, with no interference.

Hepfner and Skelly (1985) reported that patients with cochlear implants "have experienced some false auditory and temperature sensations when in the presence of electromagnetic fields." RF devices and processes include two-way radios, police radar, computer terminals, and lightning. The authors also observed that interference may occur from other electrical devices that generate sub-RF frequencies, such as light dimmers, refrigerator motors, and "electrical noise generated in a therapist's mouth by metal electrolysis in her recent dental work."

3.6.2 Metal-Rimmed Spectacles

Davias and Griffin (1989) found that metal-framed spectacles perturb microwave fields between 2 and 12 GHz. They determined this by locating a field probe (monopole antenna on a ground plane) near a human phantom composed of lossy materials that simulate tissues. The reception pattern of the probe was compared when the phantom was fitted with eyewear and when the phantom wore no eyewear. They demonstrated a difference in the radiation patterns at the field probe, where there was an increase in signal intensity when the spectacles were mounted on the phantom. Their analysis indicated that the resonant frequency of the eyewear was 900 MHz and that each of the spectacle components (wing, hook, and rim) is resonant between 1.4 and 3.75 GHz.

3.6.3 Explosion Hazards

The interaction of RF with electro-explosive devices (EED) and flammable materials may result in the ignition of materials or explosions. Materials such as solvents, fuels, and flammable gases may be ignited if the RF intensity is sufficiently high, there is a receiver of the RF energy (some conductive structure), and there is the potential for spark discharge of sufficient energy into a flammable atmosphere. In structures such as piping, stacks, and cranes, a spark discharge may occur if there is "a discontinuity in the structure which provides an intermittent electrical contact" (Maddocks 1992). For EED activation, the RF field must be sufficiently intense, and the EED must be in a position to absorb energy from the RF field (Sastradipradja and Joyner 1990). Obviously, secondary to the event, RF-induced explosions or ignitions may produce physical trauma and property damage.

Osepchuk (1992) has pointed out that a hazard unique to microwave heating is superheating of small objects. This may occur when a material is heated above the boiling point, with a rapid expansion of the superheated material resulting in a small explosion.

Table 3-17. Limitations in Biologic Effects Studies

- Differences in experimental methods
- Lack of replication of results
- Lack of establishment of mechanisms for measured end points
- Predominantly far-field experiments; relatively few data in the near field
- Animal data: primarily 915 & 2450 MHz
- Rodents used to model thermal stress are fur-bearing and do not sweat
- Epidemiologic data: no measured dose or exposure level
- Different approaches—Eastern scientists: field-based & clinical evaluations; Western scientists: primarily animal studies

3.7 CONCLUSIONS

This review of the biologic-effects literature indicates there is a good deal of information supporting the existence of thermal effects of radio-frequency and microwave radiation, including cataract formation, changes in animal behavior, and effects on reproduction and development. However, even well-established thermal effects may appear to be equivocal when experiments are performed near the threshold of effects. Although the data base has grown substantially over the past decades, much of the information concerning nonthermal effects is generally inconclusive, incomplete, and sometimes contradictory. Studies of human populations have not demonstrated any reliably affected end point.

Some general limitations of research on the biologic effects of RF fields are listed in Table 3-17. Additionally, the Advisory Committee on Nonthermal Effects of Nonionizing Radiation of the National Research Council has offered constructive criticism of research in this field (National Research Council 1986).

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United States Environmental Protection Agency

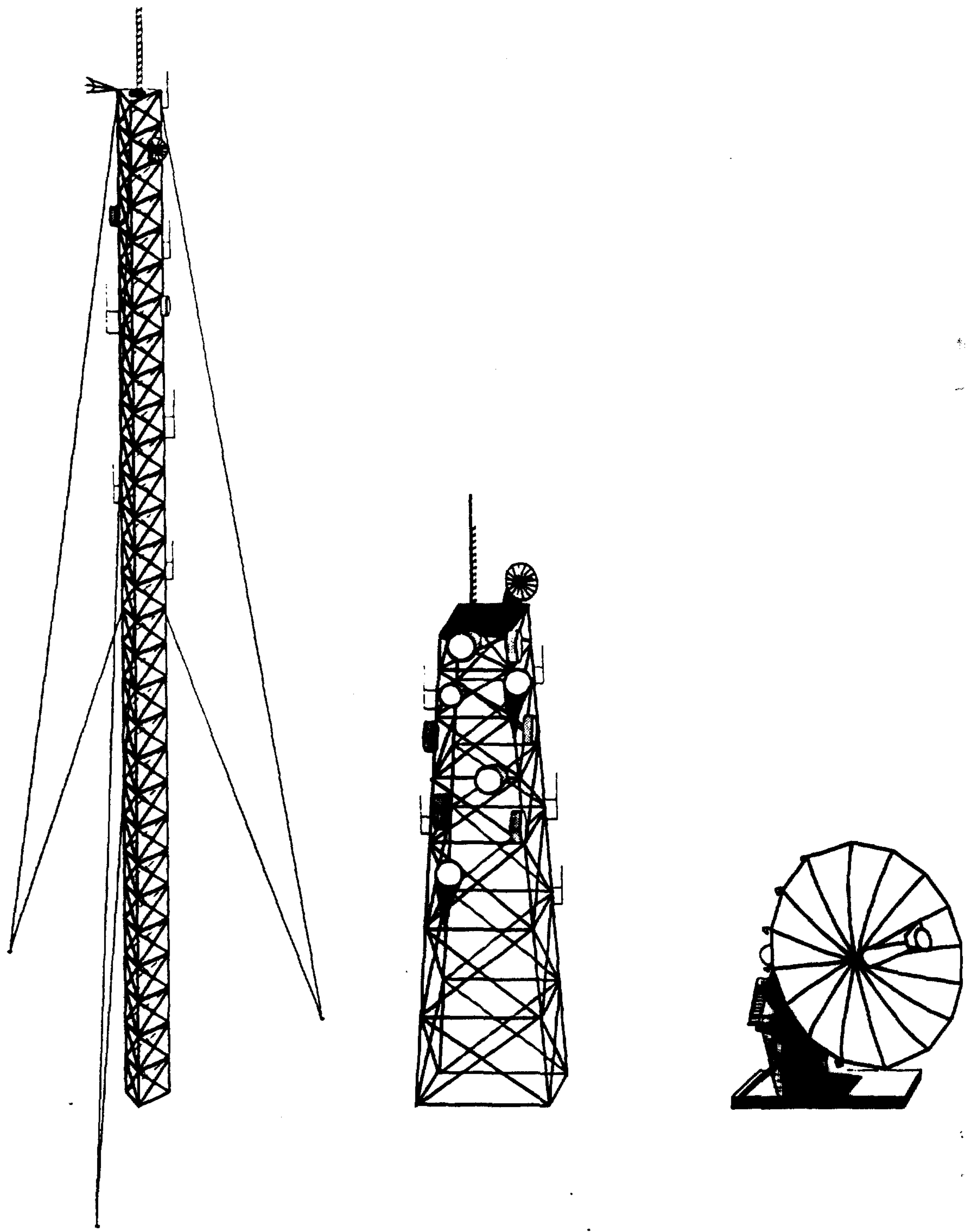
Office of Air and Radiation & Office of Research and Development

402-R-95-011
March 1995

EPA

Summary and Results of the April 26-27, 1993 Radiofrequency Radiation Conference

Volume 2: Papers



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Volume 2: Papers

Prepared for

Office of Air and Radiation
and Office of Research and Development
U.S. Environmental Protection Agency
401 M Street, SW
Washington, DC 20460

Under Contract

Nos. 68-D0-0102 and 68-D2-0177

DISCLAIMER

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ABSTRACT

On April 26 and 27, 1993, the U.S. Environmental Protection Agency (EPA) Office of Air and Radiation and Office of Research and Development held a conference to assess the current knowledge of biological and human health effects of radiofrequency (RF) radiation and to address the need for and potential impact of finalization of federal guidance on human exposures to RF radiation. More than 200 people attended the conference. Attendees represented the federal government, academia, the private sector, trade associations, the media, and the public. Plenary papers presented at the meeting focused on current research findings on a variety of topics, including exposure assessment, dosimetry, biological effects, epidemiology, the basis for exposure limits, and emerging health issues. Panel discussions focused on identifying key scientific information needs for and the policy implications of the development of further EPA guidance on human exposures to RF radiation. This document, Volume 2, provides the plenary papers presented by speakers. Volume 1, under separate cover, provides a record of much of the information presented at the conference, outlines key recommendations provided to EPA by conference participants, and presents the EPA strategy for addressing RF radiation.

Two key recommendations for EPA emerged from the conference: (1) develop RF radiation exposure guidance as soon as possible, and (2) conduct additional research in a number of areas, particularly with respect to the potential for "nonthermal" effects. These recommendations were considered by EPA in its decision to proceed with the development of guidelines on human exposure to RF radiation and to develop a longer term strategy to address remaining issues. Part of this strategy has involved creating an inter-agency work group and requesting the National Council on Radiation Protection (NCRP) to assess several remaining issues. Information provided at the conference also was used as a basis for EPA comments to the Federal Communications Commission (FCC) 1993 proposal to adopt the RF radiation exposure guidelines developed in 1992 by the American National Standards Institute (ANSI) and the Institute for Electrical and Electronics Engineers (IEEE).

RF SHOCKS AND BURNS: SOME KNOWNS AND UNKNOWNS*

*Om P. Gandhi***

INTRODUCTION

Even though there is a great deal of data on currents induced in the human body for exposure to radiofrequency (RF) electromagnetic fields both for plane wave, relatively uniform exposures [1-5] and for nonuniform exposures in industrial settings [6-8] for free standing conditions as well as for conditions of contact with energized objects, the data is much more limited on RF shocks and burns [9-11]. This is due to the severity of the phenomenon. From anecdotal stories it is obvious that this can be a serious problem for people exposed to medium and high intensity electromagnetic (EM) fields. Following up on the pioneering work of Dalziel and colleagues [9, 10, 12, 13], Guy and others [14-17] have studied the threshold currents for perception and pain ("let-go") under conditions of continuous rather than intermittent contact with RF energized electrodes. Because of the potential for harm, currents for RF shocks and burns for conditions of intermittent contact were not a part of these studies and thus have not been examined. A limited amount of data is available for transient discharge or conditions of intermittent contact with energized conductors at 60 Hz [18,19]. From the limited data that we will present, it is likely that the stored energy levels needed for RF shocks and burns for transient discharge may diminish with increasing frequency up to 100 kHz, to values that are relatively independent of frequency for frequencies in excess of 100 kHz. Since the absence of data on startle reactions by transient discharges is one of the acknowledged weaknesses of the present day ANSI/IEEE RF safety guidelines [20], it is clear that additional experimental data is needed before this important facet of RF safety is resolved.

CONTACT HAZARDS IN THE VLF TO HF BAND (10 kHz to 100 MHz)

Ungrounded metallic objects in EM fields develop open-circuit voltages which may be written as:

$$V_{oc}=E_{inc}h_{eff} \quad (1)$$

where V_{oc} is the open circuit voltage, E_{inc} is the magnitude of the incident electric field, assumed to be relatively uniform, and h_{eff} is the effective height of the object relative to the ground. Effective height of the object is related to, but is not the same as, the physical height. Effective heights of some commonly encountered objects such as a car, van, bus, fence, metallic roof, etc. have been determined and are given in the literature [14, 17]. Effective height of a car, for example, is about 0.3 m. Effective heights are even larger for bigger or higher objects such as a school bus, metallic roof, etc. For incident electric fields of a few hundred volts per meter, open circuit voltages of tens to hundreds of volts may therefore be created between the object and the ground. Upon touching such an object, a current would flow through the human body whose magnitude will depend on the conditions of contact (contact area, grounding of the body, etc.). Chatterjee, et al. [17] did a study in which the body impedance and threshold currents needed to produce sensations of perception and pain were measured for 367 human subjects (197 males and 170 females of various age groups; 18-35, 36-50 and 51-70 years) for the frequency range 10 kHz to 3 MHz. The study included various types of contact such as finger contact (contact areas 25 and 144 mm^2) and grasping a rod electrode (diameter = 1.5 cm, length = 14 cm) to simulate the holding of the door handle of a vehicle. The experimental data were used to develop graphs of average threshold incident electric fields that will cause the various sensations such as perception, let-go

* This paper was updated in October 1994.

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(pain), or even burns for adult males and females [17, 21, 22]. Predictions were also made, based on scaling, for the corresponding threshold values for ten-year old children, since the currents for perception and pain were found to be proportional to the (contact area)$^{1/4}$. Taken from reference 17, a representative graph of the threshold incident electric fields for let-go (pain) for grounded adult males and ten-year old children for finger contact (contact area = 25 mm^2) for various vehicles is given in Figure 1. For most of the cases the electric fields are lower than the maximum permissible exposure (MPE) limits given in the ANSI/IEEE C95.1-1992 [20] both for controlled and uncontrolled environments. Given in Figure 2 are the estimated incident electric fields for a wider area grasping contact that will result in currents needed for perception at various frequencies [17]. Average perception currents measured for 197 males for grasping contact with a cylindrical metallic rod of diameter 1.5 cm and length 14 cm (to simulate holding of a handle bar of an automobile) were used to estimate the incident electric fields that will result in such currents for grounded conditions of the subjects. Even though the RF source available at our disposal did not permit us to measure the currents for let-go under grasping contact conditions, we estimate these to be 25 to 30 percent larger than those needed for perception. This would imply that the threshold electric fields needed for let-go for grasping contact conditions would be 25 to 30 percent larger than the values given in Figure 2. From reference 17, perception is one of tingling/pricking sensation at frequencies lower than 70-100 kHz and one of warmth at the higher frequencies. Perception/let-go currents are relatively independent of frequency for frequencies higher than 100 kHz to 50-100 MHz [17, 23].

SHOCK, FIBRILLATION, AND BURNS

Shock and ventricular fibrillation have been discussed at length in the literature [10, 24-27] for 60 Hz currents. A review of the literature is given in [28]. The values for painful shock and ventricular fibrillation are presented by Dalziel for frequencies up to 10 kHz [13, 26]. It is believed that at higher frequencies, fairly large currents can pass through a human being without causing muscle or nerve stimulation [29]. These currents would, however, produce heating effects in the skin as well as damage to internal organs [25]. Becker et al. [30] and Dobbie [31] have reported values of RF currents which produce burns. Becker et al. [30] claim that 200 mA for 30 seconds produced reddening of the skin of an arm or hand of each of four human subjects, 300 mA for 20 seconds produced pain and blistering, and 400 mA for 10 seconds produced unbearable pain. In each case, the electrode was a 3.8 cm^2 disposable silver ECG electrode. Also, 400 mA through a 1 cm^2 Ferris Red Dot disposable electrode for 20 seconds produced a second-degree burn on the back of a subject's hand. This study was in reference to electrosurgery and so the frequency, though not stated in [30], is assumed to be around 500 kHz. From our results on perception and pain threshold currents beyond about 100 kHz [17], it is expected that the threshold currents for burns at other frequencies would not be any different. Dobbie [31], studying burns during surgical diathermy, reports that 100 mA through a needle electrode used in ECG monitoring over the deltoid muscle causes a unpleasantly hot sensation in 10 seconds. Becker et al. [30] report that 100 mA per square cm of skin for 10 seconds using ECG electrodes produced a burn.

Our measurements of threshold pain current on 197 male subjects indicated that an average current density of approximately 192 mA/cm^2 for contact with the front of the index finger for frequencies greater than or equal to 100 kHz, caused discomfort for a contact area of 25 mm^2. We believe that this current density would definitely have caused a burn had the subject been told to keep touching the copper plate.

It has previously been mentioned that the threshold current for perception varies with the fourth root of the contact area [17]. It is expected that the threshold current for burns will also follow the same relationship with respect to the contact area, i.e., the current density will vary as (area)$^{-3/4}$. For the previously studied contact areas of 144 and 25 mm^2, the burn thresholds can therefore be obtained by scaling 100 mA/cm^2 needed to cause RF burns [30], according to the relation, burn threshold current density = (area)$^{-3/4}$. This gives a current density of 76 mA/cm^2 for a contact area of 144 mm^2 and 283 mA/cm^2 for 25 mm^2.

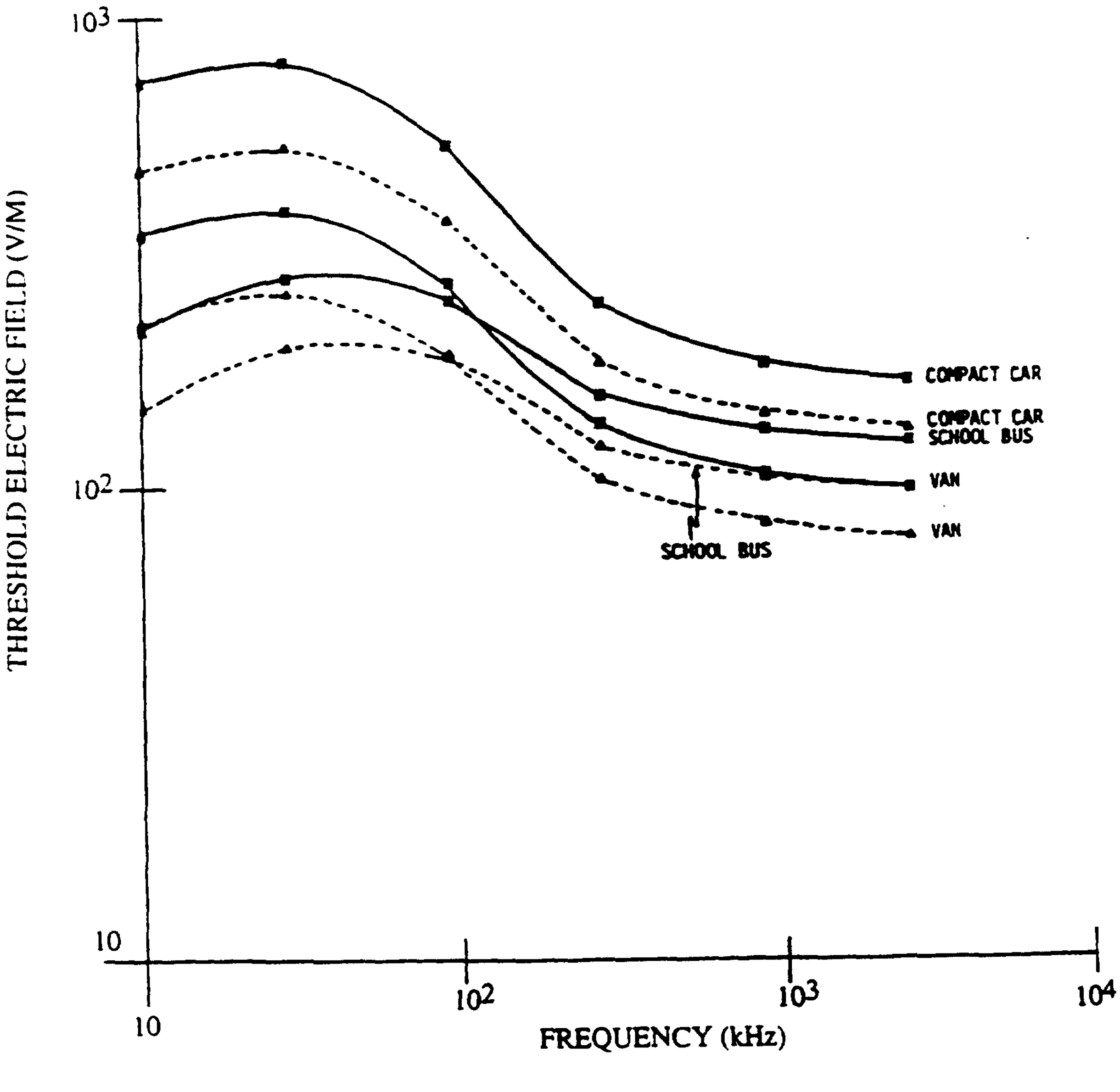

Fig. 1. Average threshold electric field for let-go (pain) for grounded adult males (solid curves) and ten-year old children (dashed curves) in finger contact with various vehicles. Contact area = 25 mm^2.

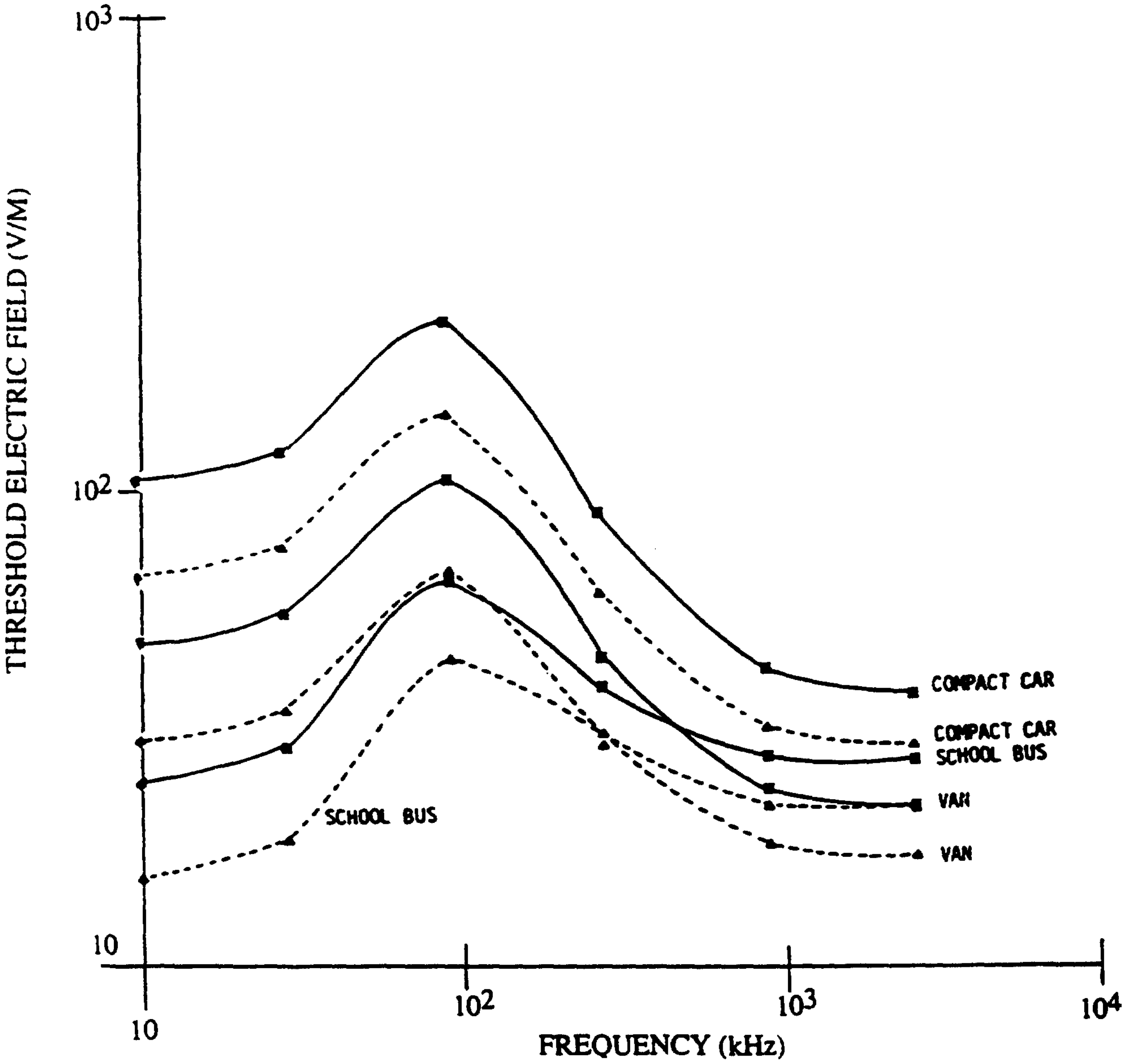

Fig. 2. Average threshold electric field for perception for grounded adult males (solid curves) and ten-year old children (dashed curves) in grasping contact with various vehicles.

The calculated results for threshold E-fields to cause RF burns are plotted in Figures 3 and 4 for male adults and ten-year old children for contact areas of 25 mm^2 and 144 mm^2, respectively. Since the data are not available for children, the threshold fields for children are obtained by scaling the impedance of male adults by the ratio of the height of a standard 50th percentile ten-year old child (1.38m) to the height of a standard 50th percentile male adult (1.75m) and by scaling the burn threshold current for male adults by the square of the ratio of the height of a ten-year old child to the height of a male adult.

TRANSIENT DISCHARGES

A deficiency acknowledged in the ANSI/IEEE C95.1-1992 safety guidelines [20] is that the current limits prescribed for induced and contact currents [Tables 1 and 2, parts B of ref. 20] "may not adequately protect against startle reactions caused by transient discharges when contacting an energized object". In many situations, the hazard of transient discharge may well be the most important issue for safety. Involuntary muscular reactions to transient spark discharges can cause many safety hazards. In our evaluation of construction worker safety at a U.S. Coast Guard Omega Transmitting Station (10.2-13.6 kHz), in collaboration with Robert Curtis (OSHA) and Gene Moss (NIOSH), we found that thresholds of perception, annoyance, and even spark discharges were easily exceeded for intermittent contacts with ungrounded objects (such as cables, metallic tubes, etc.) exposed to RF fields. These, of course, were a result of the energy storage (CV^2_{rms}) in these objects that could be discharged upon touching or at times even approaching these objects. Another interesting observation was that the perception threshold for finger contact for the Omega site (10.2-13.6 kHz) occurred for stored energy levels on the order of 15-20 μJ which is considerably lower than 100-150 μJ (depending on capacitance C of the objects) which is estimated at 60 Hz by experimentation with two subjects [18]. This leads us to believe that the stored energy for perception, annoyance, and spark discharges may be frequency dependent with values being considerably lower at higher frequencies than at 60 Hz where most of the data are presently available. This point of view is also shared by Dr. A. W. Guy [personal communication] who has some unpublished data at 23 kHz and feels that the perception threshold for stored energy may be even lower than 15-20 μJ that we estimate for 10.2-13.6 kHz. In another paper by Delaplace and Reilly [32], data are presented to show that threshold of spark discharge is related to energy (CV^2_{rms}) for capacitance less than 575 pF and charge (CV^2_{rms}) for $C > 575$ pF. From these limited data, most of which are at 60 Hz, it is obvious that much more data need to be obtained on the stored energy levels for transient spark discharge at various frequencies.

CONCLUDING REMARKS

Possibility of RF shocks and burns is a serious problem for personnel working close to high power transmitting antennas in the low, medium, and high frequency bands. Even though a great deal of data is available for threshold perception and let-go currents, the stored energy levels that will result in startle reactions or burns for transient discharges for intermittent contacts are not known. Some limited data points to the possibility that stored capacitive energies needed for transient discharge are likely to decrease with increasing frequencies. Since startle reactions caused by transient discharges may result in accidents, this data and instrumentation to assess which of the objects may pose such a hazard are urgently needed.